AD/A-005 055

# DEVELOPMENT OF AN AIRCRAFT BATTERY CONDITIONER/ANALYZER

Chrysler Corporation

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Army Air Mobility Research and Development Laboratory

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## EUSTIS DIRECTORATE POSITION STATEMENT

This Directorate concurs in the findings presented in the report and recommends that the findings be considered for inclusion in the design and development of improved helicopter battery systems. Although precise quantitative results were not available, the testing supporting this program has provided highly responsive trend data.

The work described in this report is part of a continuing program to increase the useful life, availability, and reliability, and to decrease the life-cycle cost and maintenance, of battery systems in Army aircraft. It is expected that this report will be used as a basis for other work being done in similar areas by USAECOM and USAAVSCOM. Currently USAAVSCOM is considering the purchase of six or eight similar but less sophisticated chargers in an evaluation program to improve aircraft battery safety.

Mr. Thomas Allardice of the Military Operations Technology Division served as Project Engineer for this effort.



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This report documents the development and evaluation of a prototype Programmed Peak Charges (PPC) battery conditioner/analyzer system for nickel-cadmium batteries. It describes testing to determine the advantages of the unit as compared to constant-potential-charge systems. The results show that the PPC system reduces water boiloff, reduces overtemperature conditions, and has fewer battery recycles and cell replacements. Use of the PPC system increases battery life, reduces maintenance, and eliminates hazards.

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## PREFACE

This report documents the results of the work performed by Chrysler Corporation Space Division (CCSD) on the development of a Battery Conditioner/Analyzer under Contract DAAJ02-72-C-0108. The unit has the capability to charge a battery as used in helicopter flights and to analyze the condition of the battery and display the state of charge (SOC) as well as other pertinent parameters.

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## INTRODUCTION

Chrysler Corporation Space Division has developed and evaluated a prototype conditioner/analyzer system for nickel-cadmium (Ni-Cad) batteries.

The Battery Conditioner/Analyzer (BAC) is capable of: (1) programming battery charge current in a predetermined tri-level current profile, (2) analyzing the status of the battery by measurement and computation of temperature, state of charge (SOC), etc., and (3) displaying battery status and other system parameters.

The objectives of the program were to design and evaluate a system that would provide the following improvements in system characteristics:

- Increased Safety
- Reduced Maintenance
- Reduced Cost
- Increased Operational Capability

To facilitate attainment of these objectives, the program was divided into the following phases:

- Phase I - System Design
- Phase II - Component Design and Test
- Phase III - System Assembly
- Phase IV - System Test
- Phase V - System Documentation

## EQUIPMENT REQUIREMENTS

### GENERAL REQUIREMENTS

Requirements for the BAC prototype unit were based on the following:

- o Must be capable of operating with nominal 24v, lead-acid or Ni-Cad, vented cell batteries with nominal capacity of 34 ampere-hours.
- o Must be capable of programming battery charging in a predetermined manner.
- o Must be capable of operating with current shunt in positive output side of battery instead of negative side.
- o Must be capable of analyzing the status of the battery and provide a display of battery and power system parameters.
- o Must be capable of transferring the battery to the DC bus and stop the charger when bus voltage drops below predetermined level.
- o Must resume battery charge when bus voltage reaches a predetermined level.

### CONDITIONER/ANALYZER ASSEMBLY

To meet the overall requirements, the conditioner/analyzer assembly was designed to meet the following requirements:

- o Power Input - 3-phase, 4-wire, 115/200v, 400 Hz or 24v DC from the battery with AC power off.
- o Power Output - The charger output is capable of adjustment to automatically provide the three-step volt-amp characteristic shown in Figure 12 when operated into a battery.
- o Battery Power Transfer Circuit - This circuit has the capability of transferring the battery to the DC bus and terminating charge when the bus voltage drops below a predetermined value. Circuit must have capability of 40A continuously or 400A peak.
- o Capable of controlling battery state-of-charge (SOC) in accordance with Figure 1. A switch to set the SOC readout to 100% when desired.

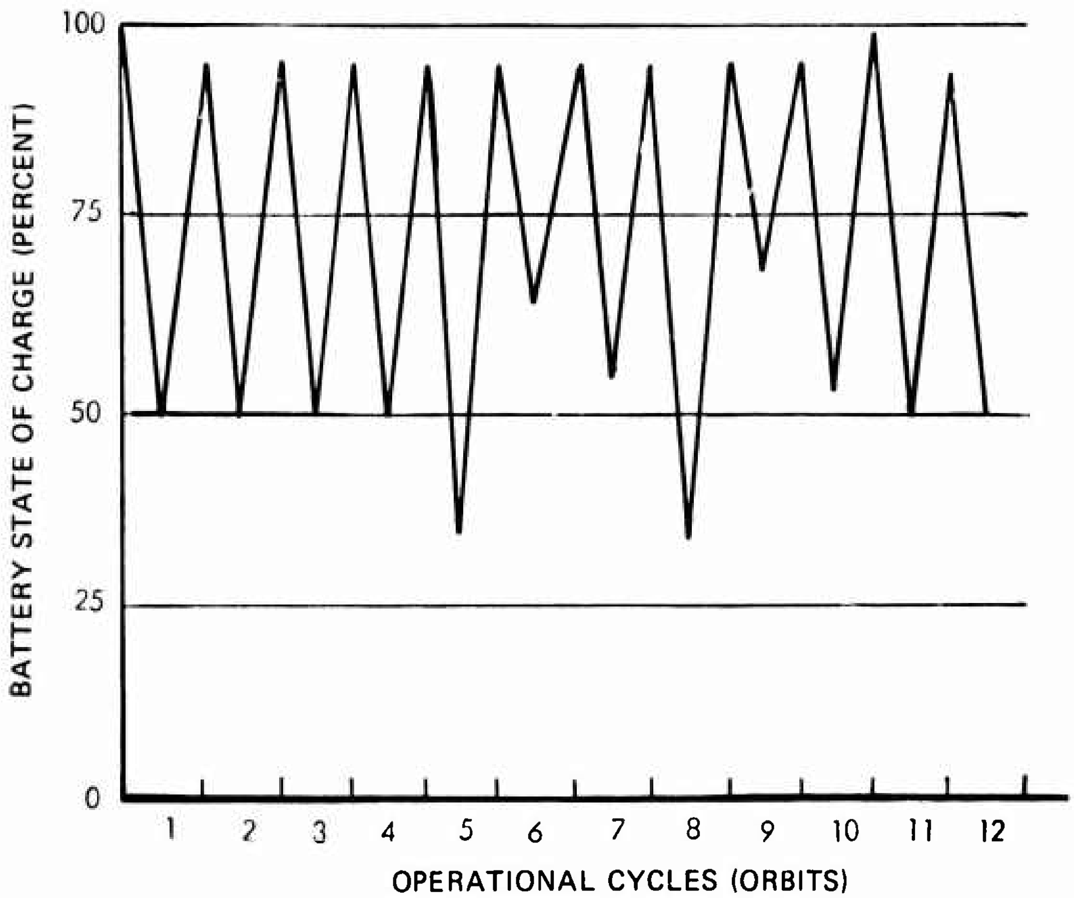


Figure 1. Programmed Peak Charge Variations Produced by PPC Method.

- o State-of-charge circuitry to determine SOC to within ± 10 percent over a 10-cycle period. Capable of compensating for the effect of the following parameters on SOC:

  - o Stand time loss
  - o Charge efficiency
  - o Capacity - temperature
  - o Capacity - cycle life

- o Temperature compensation for charge voltage limits - adjustable up to 0.25 volt/cell.

- o Charge current limits adjustable with potentiometer inside assembly to following limits:

| Rate | Limit |
|---|---|
| Initial | 0.5C to 1.0C |
| Intermediate | 0.2 to 0.5C |
| Trickle/Equalize | 0 to 1.1C |

- o Battery and charger protection for the following parameters by inhibiting charging.

  - o Battery temperature above 120°F
  - o Battery voltage above 29.5v
  - o Battery voltage switched to voltage bus

DISPLAY ASSEMBLY

The display assembly was designed to meet the following requirements:

- o Input Power - Required power as supplied by conditioner/analyzer assembly.

- o Input Signal - Capable of accepting 16 input signals. The range of the signals can be as follows:

| | | Quantity |
|---|---|---|
| Battery cycles | 0-400 | 1 |
| DC voltages | 0-50VDC | 2 |
| AC voltages | 0-150Vrms | 7 |
| Frequency | 400±10% | 3 |
| DC current | ± 50 amps | 1 |
| SOC | 0 to 110% | 1 |
| Battery temperature | -55 to +55°C | 1 |

o Data processed with the following accuracies.

| Parameter | Accuracy |
|---|---|
| Cycles | $\pm$ 2% |
| DC voltages | $\pm$ 2% |
| AC voltages | $\pm$ 4% |
| Frequency | $\pm$ 1% |
| DC current | $\pm$ 2% |
| SOC | $\pm$ 10% |
| BAT temp | $\pm$ $5^{o}$C |

o Scan Rate - Each parameter for 4 seconds. Dwell time less than 0.1 at max scan rate.

o Mode Select - Capable of the following three modes of operation.

a. Normal - Scan and display all parameters

b. Exception - Display only abnormal parametric data

c. Manual - Display selected parameter

o Controls - Controls for the BAC and Display assembly and their functions are identified in Tables 1 and 2.

Table 1. Conditioner/Analyzer Controls List

| NAME | POSITION | REMARKS |
|---|---|---|
| Cycle Reset | Reset | Reset cycle count readout to zero. |
| | Operate | Normal operation of cycle count readout. |
| SOC Reset | SOC Set | Set SOC readout to 100% during initial mating of BAC to battery or whenever desired. |
| | Normal | Position for normal operation. |

Table 2. Display Controls List

| Name | Position | Remarks |
|---|---|---|
| Mode Select | Manual | Display continuously monitor channel being displayed when placed in manual position. The display will advance one channel each time the "Advance" push-button is depressed (a maximum of 5 sec is required to change channels). |
| | Normal | Display continuously scan all channels in sequence (each channel display is between 3 and 5 sec). |
| | Exception | Only channels with out-of-tolerance conditions are displayed. |
| Channel Advance | Depress-to-Advance | Advance display one channel when in man. mode on toggle switch. |

## EQUIPMENT DESCRIPTION

### BATTERY ANALYZER/CONDITIONER (BAC) SYSTEM

The BAC system is shown in Figures 2, 3, and 4. The system includes the following:

- o Conditioner/Analyzer Assembly
- o Display Electronic Unit
- o Display Unit
- o Temperature Sensor
- o A Power Transfer Circuit

The interconnection of the above system is shown in Figure 5. The connector pin functions are identified in Table 3.

### Conditioner/Analyzer Assembly

The conditioner/analyzer assembly (see Figure 2) consists of a power section and an electronic section. The electrical schematic for the assembly is SKEE 416.

The power section converts the 3-phase, 400-Hz, 200-volt input voltage into the various voltages required by the BAC. It also contains the following:

- o Two commercially available DC-DC converters which provide +15 vdc, -15 vdc, +12 vdc, -6 vdc, and +5 vdc for the BAC electronics.
- o +34 vdc with output driven by the pulse width modulated signal from the electronic section to provide the output charge current.

The electronic section consists of 6-wire wrap type printed wiring cards (PC). It performs the various control logic, cycle counting, charge/discharge integration, and numerous other functions required by the conditioner/analyzer assembly. The cards as shown with the major components identified are shown in Figures 6 through 11. The adjustment functions are outlined in Table 4.

The electronic section provides the programming for the current and SOC charge profiles.

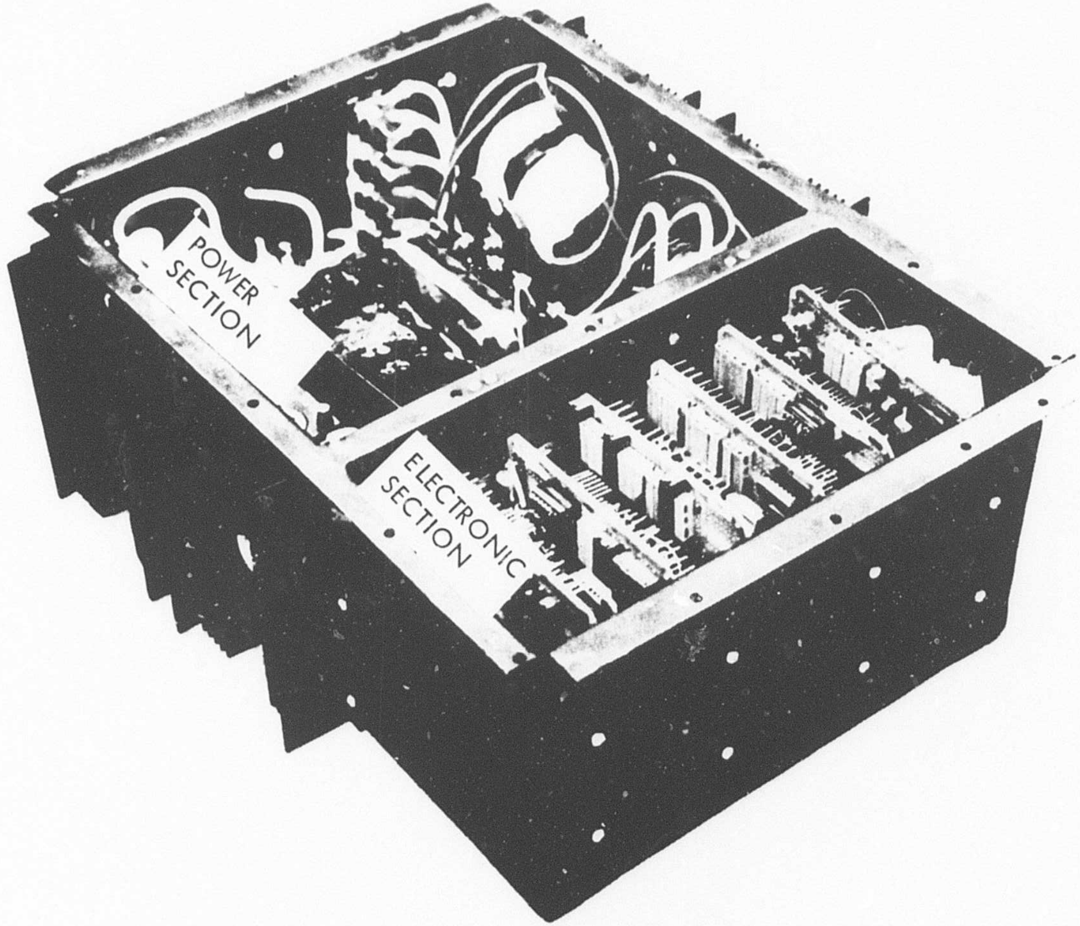


Figure 2. Battery Analyzer/Conditioner.

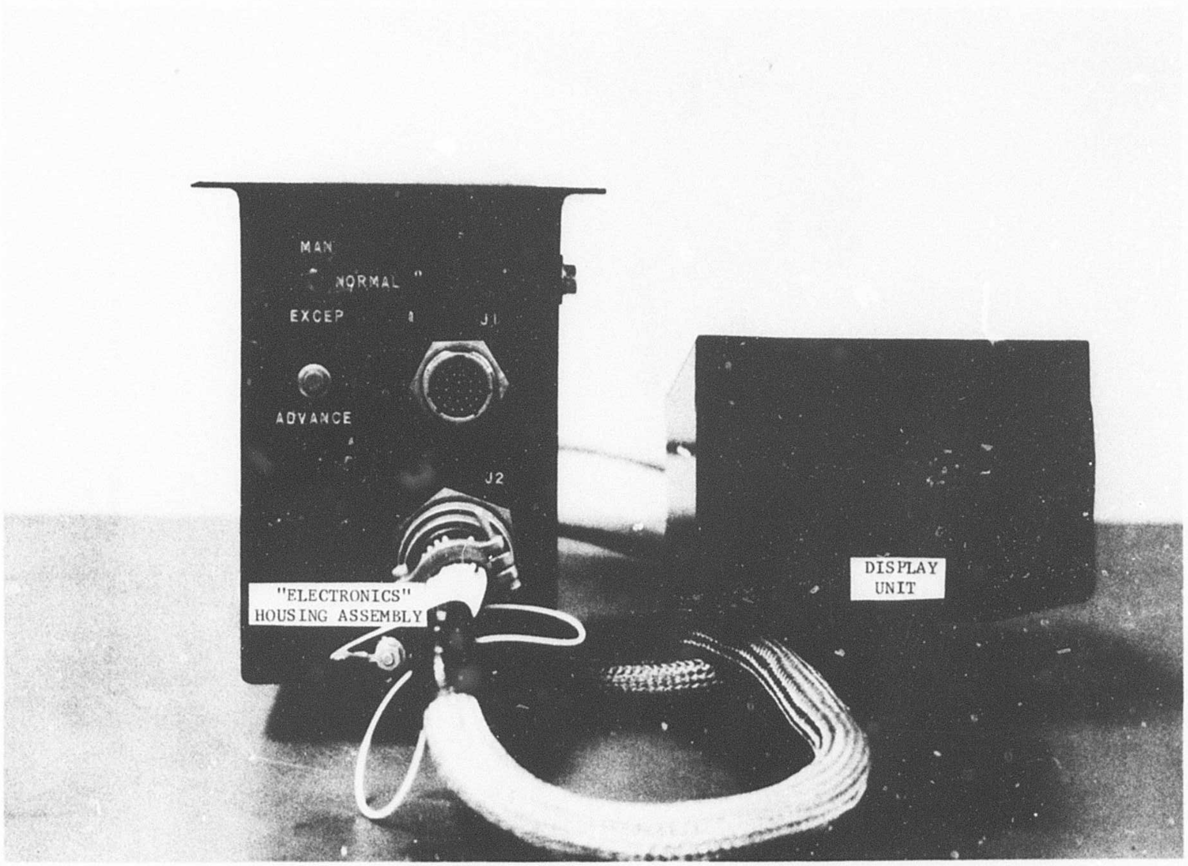


Figure 3. Electronic Assembly and Display Unit.

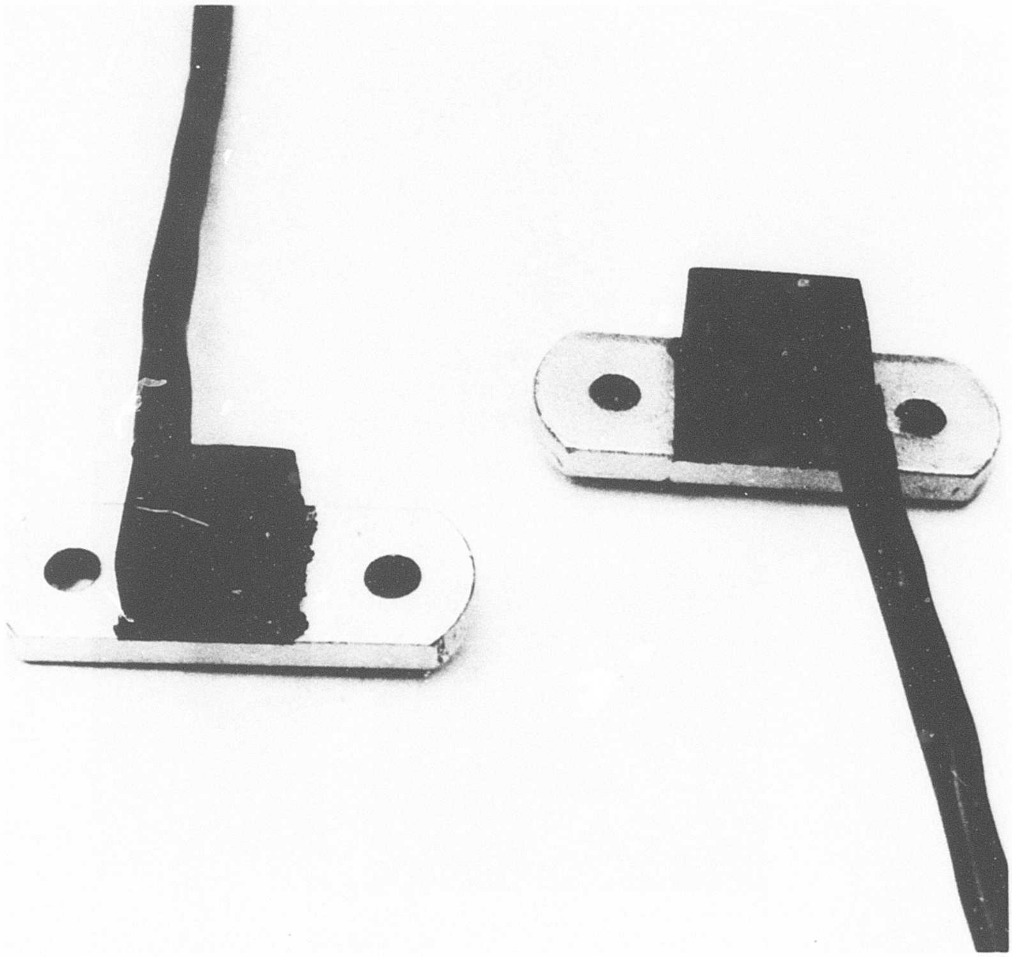

Figure 4. Temperature Sensor Assembly.

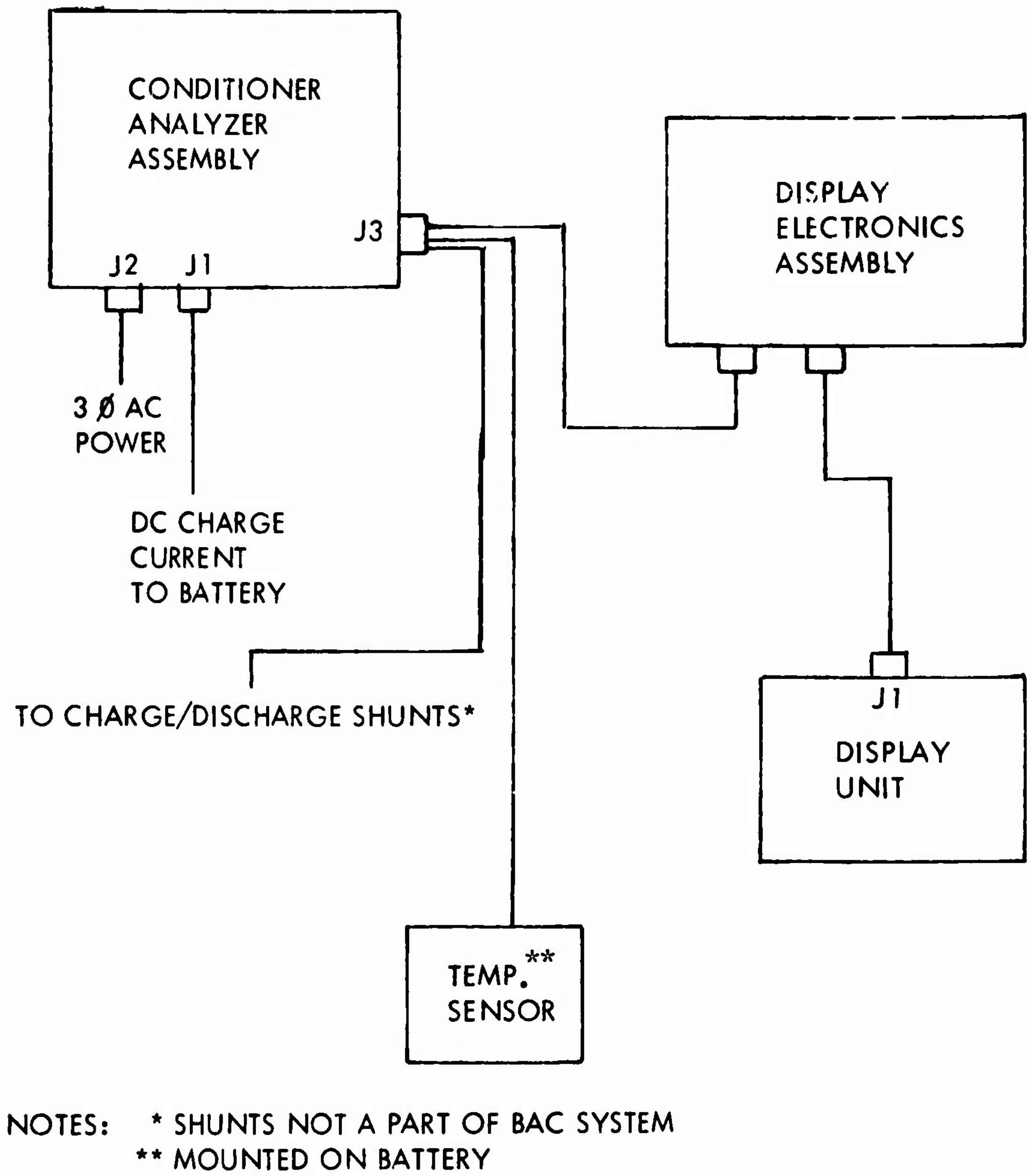


Figure 5. System Interconnection Block Diagram.

Table 3. Interconnecting Cabling Pin Function List

| Signal Description | Display | Conditioner Analyzer | Display Electronics | External Connection |
|---|---|---|---|---|
| 3 Ø Common | - | J1-A | - | AC Pwr |
| Ø A | - | J1-B | - | AC Pwr |
| Ø B | - | J1-C | - | AC Pwr |
| Ø C | - | J1-D | - | AC Pwr |
| - Battery | | J2-A | - | (-) Battery |
| + Battery | | J2-B | - | + Battery |
| 3 Ø Common | - | J3-A | J - A | - |
| Ø C | - | J3-B | J - B | - |
| Ø B | - | J3-C | J - C | - |
| Ø A | - | J3-D | J - D | - |
| + Shunt | - | J3-E | - | 50 A Shunt |
| Sig-GND | - | J3-F | J - F | - |
| -15 vdc | - | J3-G | J - G | - |
| +15 vdc | - | J3-H | J - H | - |
| + 5 vdc | - | J3-J | J - J | - |
| Cycle Count | - | J3-K | J - K | - |
| BAT Temp. | - | J3-L | J - L | - |
| BAT Current | - | J3-M | J - M | - |
| BAT Volt | - | J3-N | J - N | - |
| Bus Volts | - | J3-P | J - P | - |
| BAT SOC | - | J3-R | J - R | - |
| - Shunt | - | J3-S | - | 50 A Shunt |
| | - | J3-T | J - T | - |
| | - | J3-U | J - U | - |
| | - | J3-V | J - V | - |
| | - | J3-W | J - W | - |
| + Shunt | - | J3-X | | 750 A Shunt |
| - Shunt | - | J3-Y | | 750 A Shunt |
| | - | J3-Z | | BAT |
| Temp. Supply Pwr. (1.0v) | - | J3-a | | Temperature Sensor |
| Temp. Output Signal | - | J3-b | | Temperature Sensor |
| | - | J3-c | | |
| Display Power and J1 Logic Matrix Wind Pin to Pin | | | J 2 | |

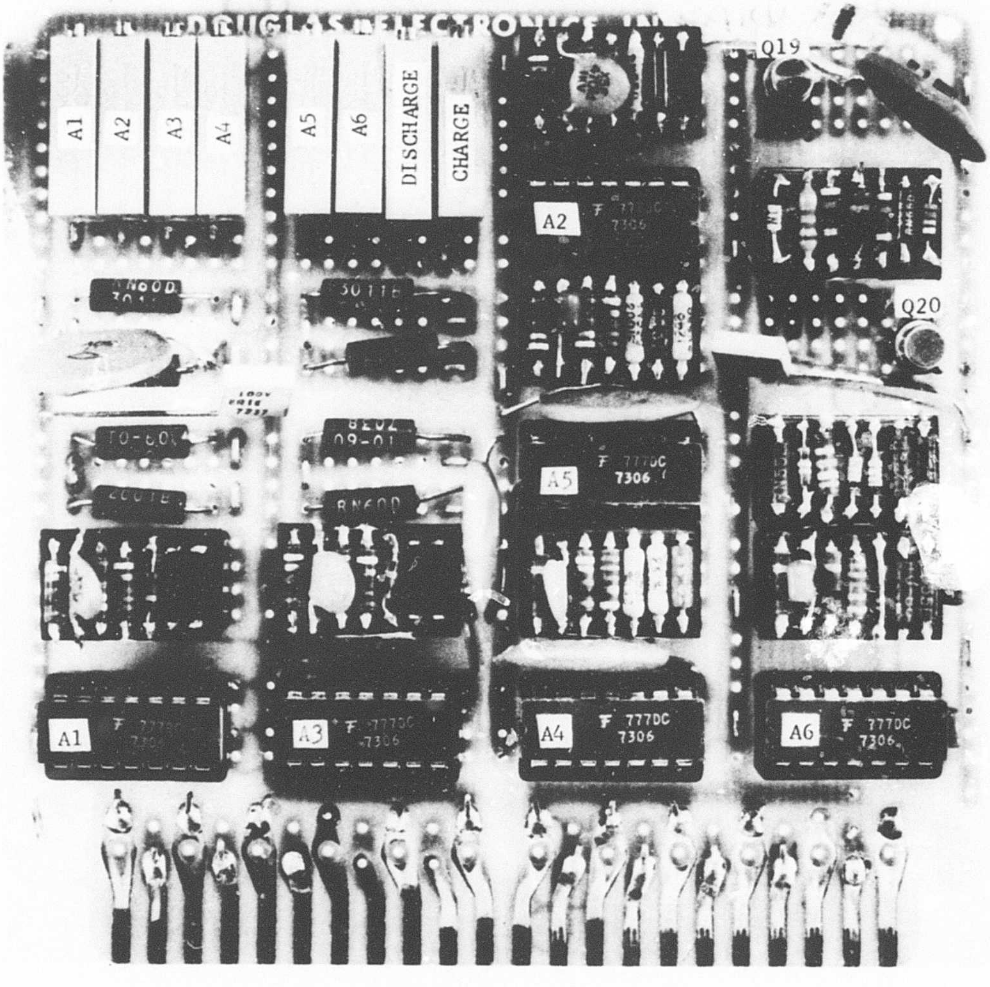


Figure 6. PC No. 1 BAC Electronics Section.

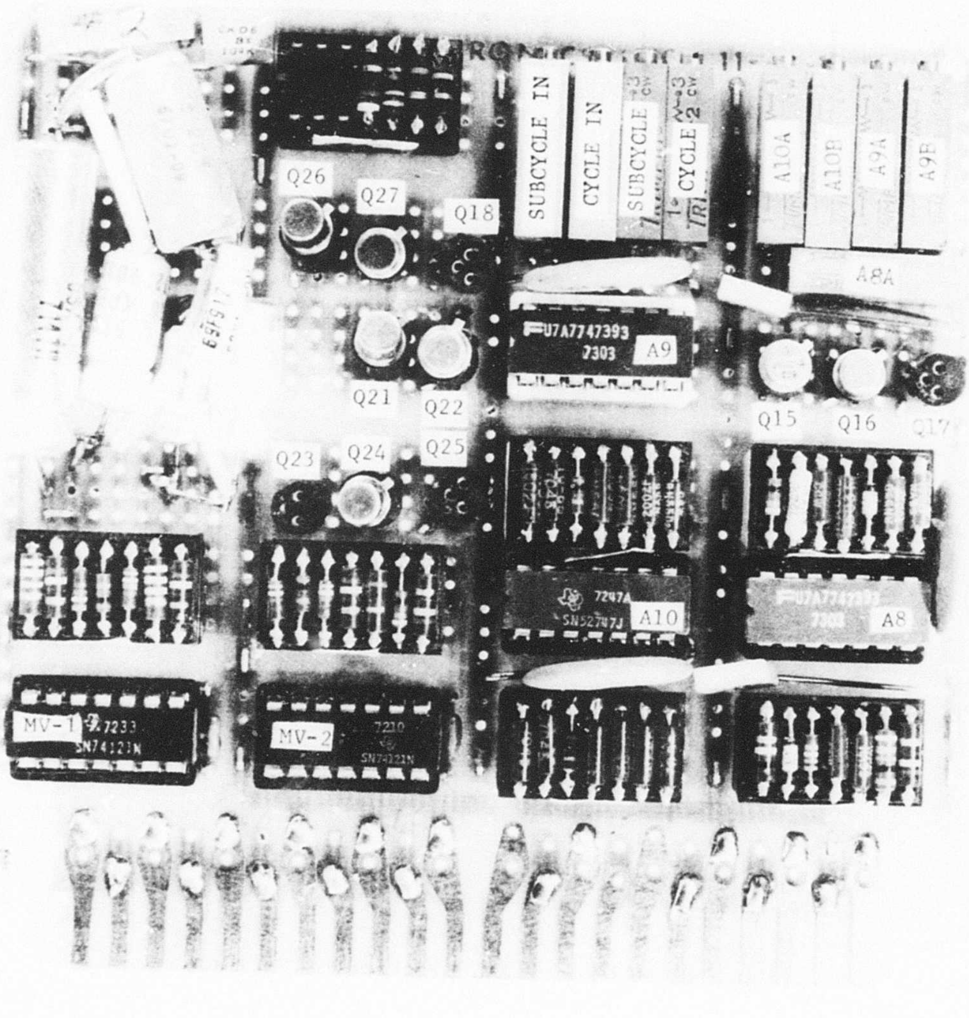


Figure 7. PC No. 2 BAC Electronics Section.

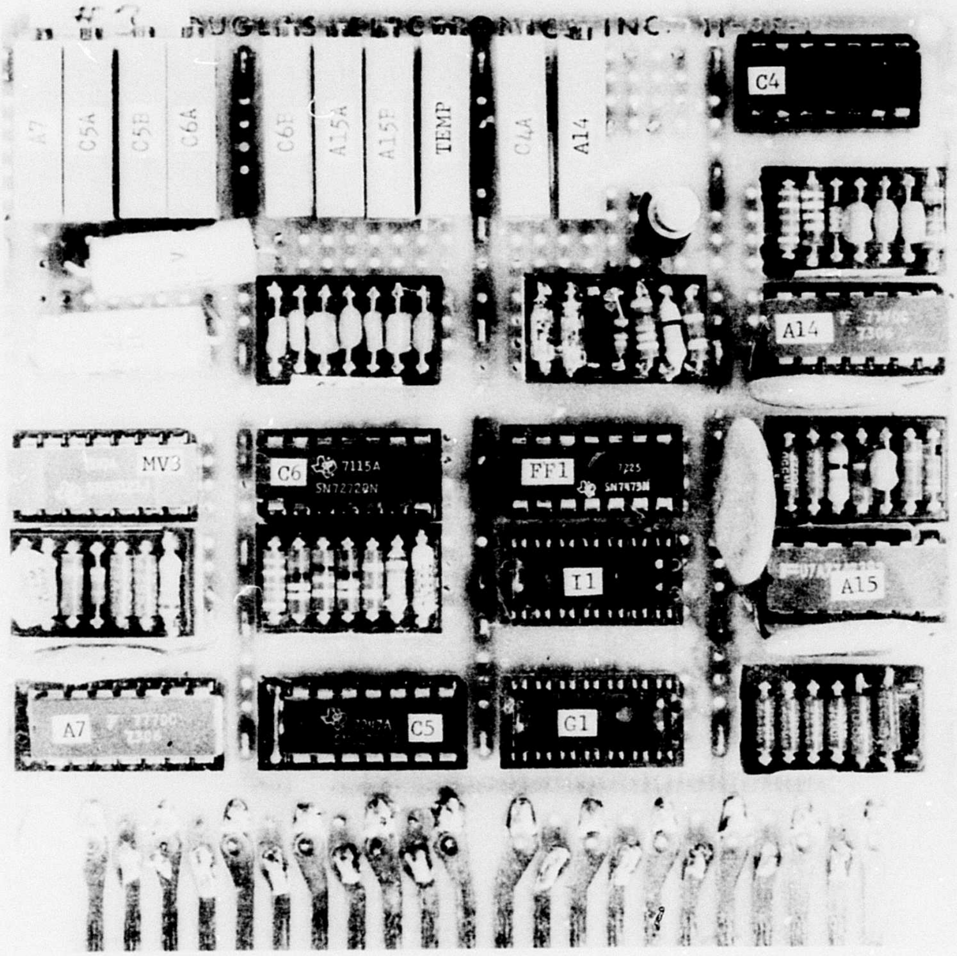


Figure 8. PC No. 3 BAC Electronics Section.

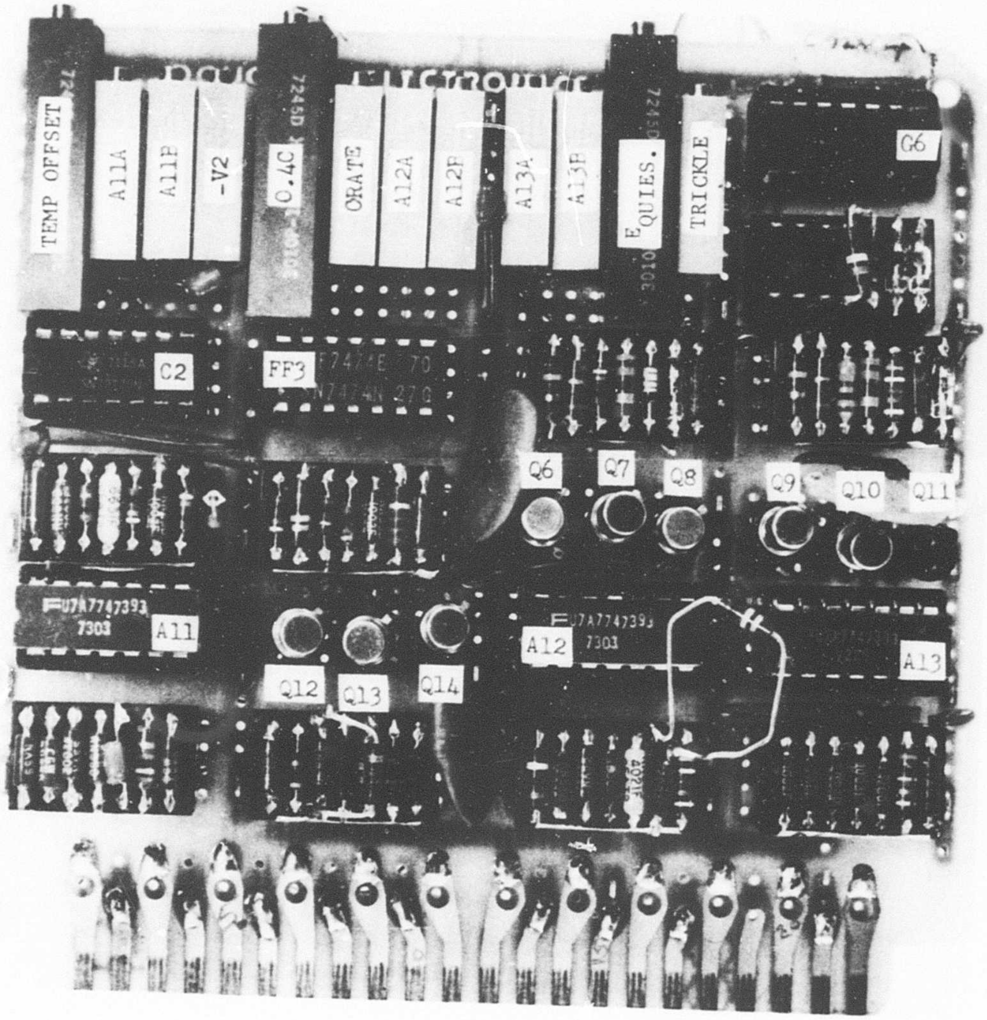


Figure 9. PC No. 4 BAC Electronics Section.

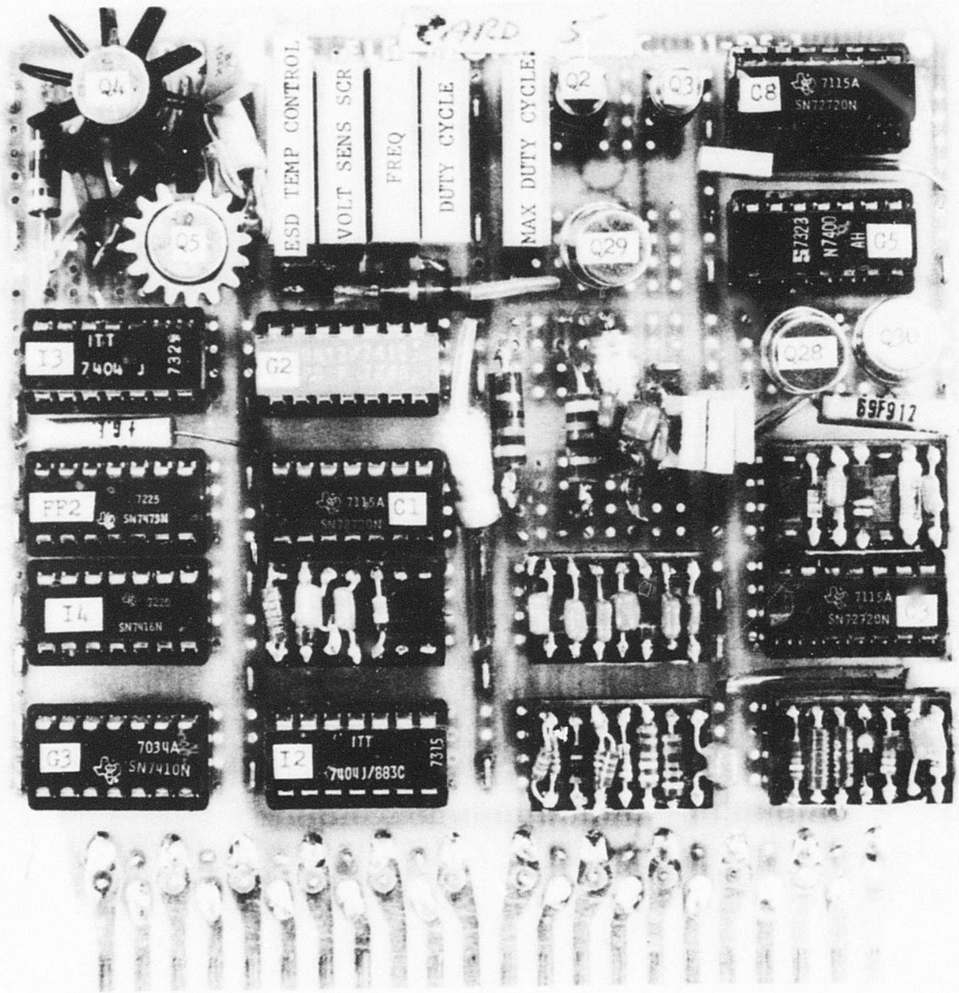


Figure 10. PC No. 5 BAC Electronics Section.

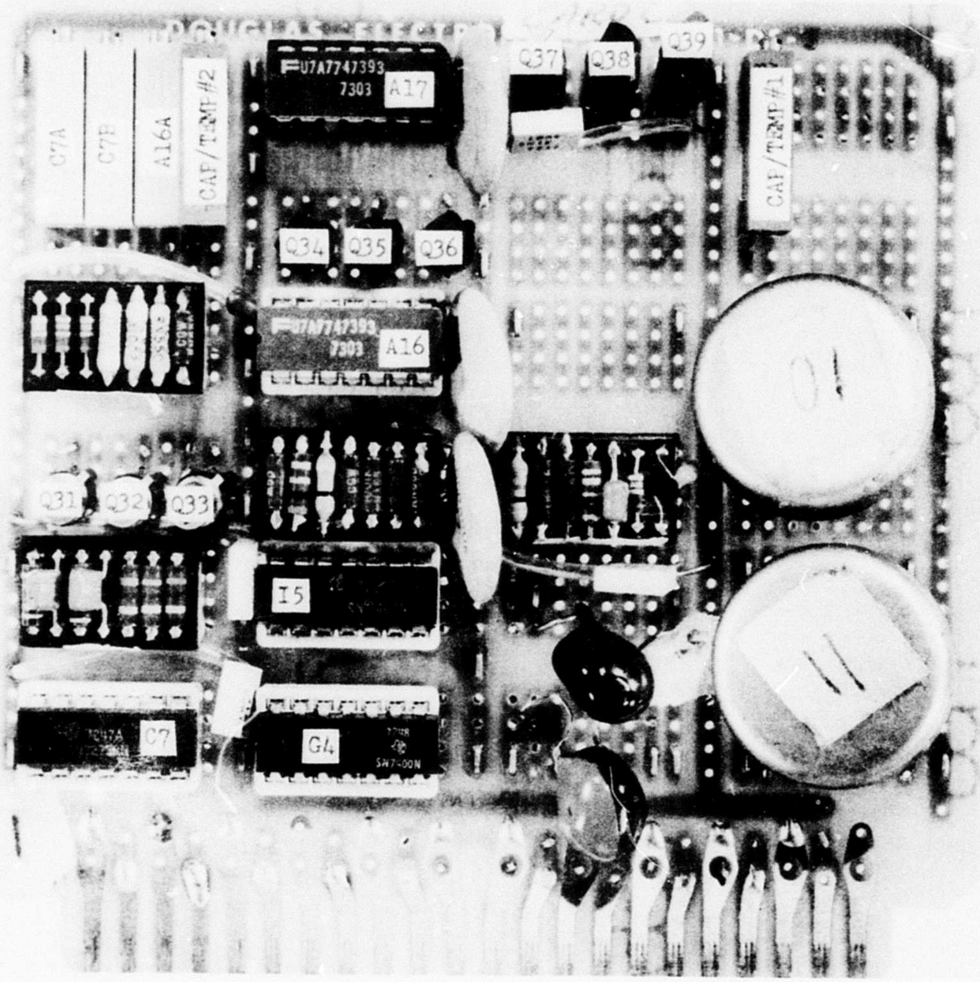


Figure 11. PC No. 6 BAC Electronics Section.

Table 4. PC Card Adjustments

| PC Card No. | Adj. Name* | Adj. Function | Remarks |
|---|---|---|---|
| PC-1 | Charge<br>Discharge | SOC Charge Rate<br>SOC Discharge Rate | |
| PC-2 | Subcycle In<br>Cycle In<br>Subcycle<br>Cycle | Input pulse amplitude<br>Input pulse amplitude<br>Voltage/pulse output<br>Voltage/pulse output | |
| PC-3 | C5A<br>C5B<br>C6A<br>C6B<br>C4A<br>TEMP | I 1 amp<br>Amt Q per subcycle<br>Adj. 90% SOC cutoff<br>Adj. 100% SOC cutoff<br>Hi Temp. cutoff<br>Temp Compensation | |
| PC-4 | $-V_2$<br>0.4C<br>C Rate<br>EQUIES<br>Trickle<br>Temp. Offset | Cutoff voltage level<br>0.4C charge rate<br>1 C charge rate<br>0 charge adj.<br>Trickle charge adj.<br>Temp. offset voltage | Do not exceed 24 amps |
| PC-5 | Duty cycle<br>Freq<br>Max duty cycle<br>Volt sensing<br>ESD Temp Con. | ESD temp control adj. | Not used |
| PC-6 | Cap Temp #1<br>Cap Temp #2 | SOC temp compensation<br>SOC temp compensation | |

NOTE* All "A" type potentiometers are for zero adjustment of the amplifiers with the corresponding number of the potentiometer.

The typical charging current/voltage versus time profiles are shown in Figure 12. Charging is started at the 0.59C rate (20 amperes) and is continued at this rate until the battery voltage reaches the transition value $V_2$ (approximately 27.6 vdc at 25°C).

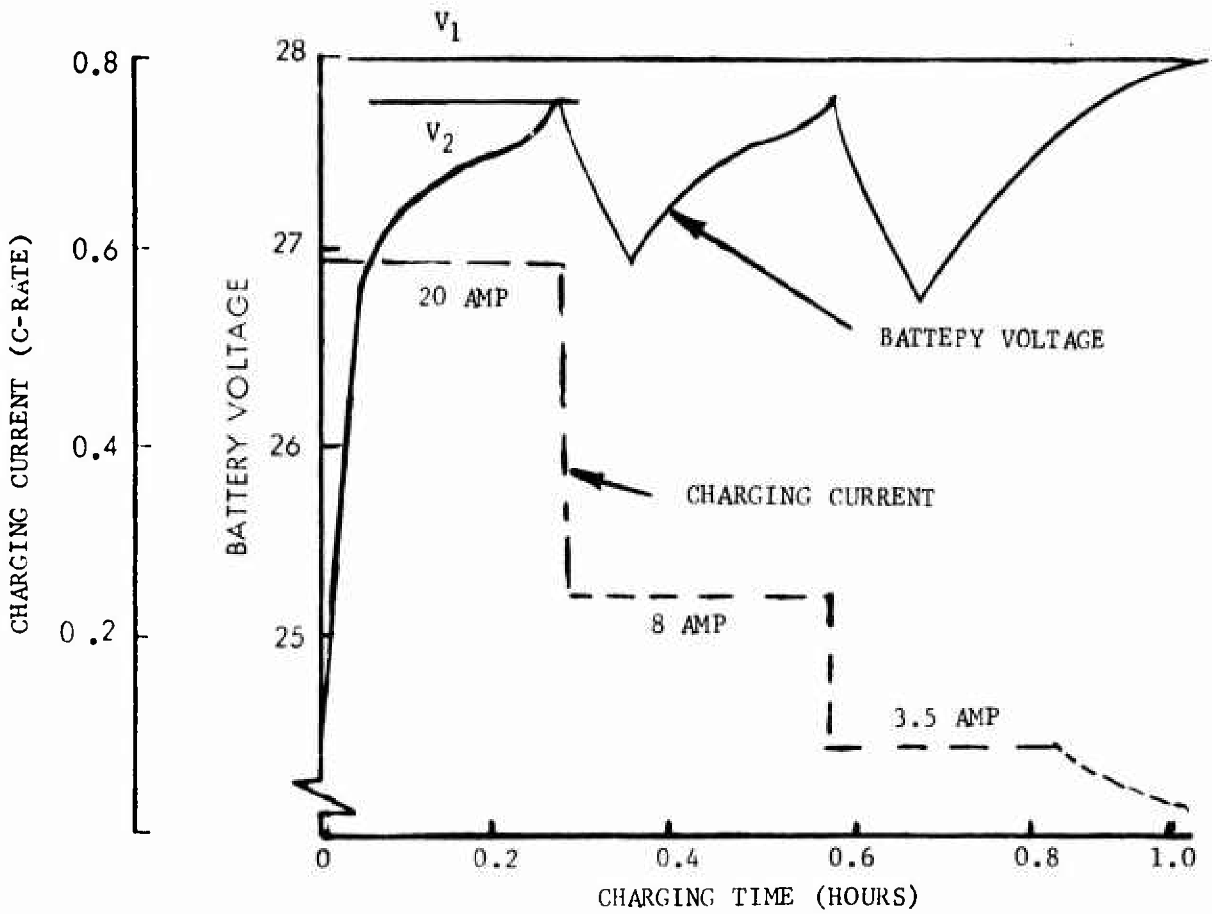


Figure 12. Charging Current/Voltage Versus Time.

When the voltage reaches the transition voltage $V_2$, the charging current is reduced to the 0.24C rate (8 adc). Charging is continued at this rate until the battery voltage again reaches the transition voltage $V_2$. At this point the charger characteristics are modified to provide a constant-current/constant-potential output. The charging current is regulated at the 0.10C rate (3.5 adc) and the battery voltage is limited to $V_1$, which is 28 vdc at 25°C. $V_1$ and $V_2$ are also temperature-compensated at the rate of minus 0.034 vdc per degree C.

During the discharge/charge cycles 1 through 9, peak SOC is limited to 92 percent. During cycles when the battery is fully charged, charging is sustained in the constant-potential region for the duration of the time allotted for charging.

A SOC computer including an ampere-hour integrator, provides the signal to stop charging during cycles when the peak SOC is limited to 92 percent. The SOC computer circuits include compensation for charge efficiency of 90 percent.

The fully-charged condition attained during the tenth discharge/charge cycle is defined as the point at which the charging current drops to 1.0 adc in the constant/potential portion of the profile shown by Figure 12. When this point is reached the integrator circuit is reset to correspond to 100 percent SOC.

Another integrating circuit including two stages is used for counting discharge/charge cycles. The first stage counts from 0 to 10 and provides signals to the control circuits and to the second stage of the cycle-counting circuit. The first stage signal to the logic and control circuits is used to program peak battery SOC. The first-stage counter is reset to zero after the count of 10 is reached. A cycle is defined as occurrence of charging current at the 0.59C rate.

The second cycle-counting stage counts in increments of 10 to a total of 400 cycles. The second stage output is provided as an indication of the battery history that can be used to determine the need for reconditioning or replacing the battery.

The battery SOC signal computed in the manner described previously is modified so as to reflect battery capacity. The circuits compensate the SOC signal to account for the effects of temperature and discharge/charge cycles on battery capacity.

The compensation factor for battery capacity as a function of discharge/charge cycles is 0.2 percent per cycle.

The constants of the capacity computing circuits are such that an analog signal of 1.0 vdc is provided for a fully-charged new battery at nominal temperature.

Other signals related to battery temperature, voltage, charging current, and discharge current are generated with conventional circuits to indicate the system status. A circuit is also included to turn off the charger in the event that battery temperature exceeds $140^{o}F$ or the output voltage exceeds 29.8 vdc.

The assembly converts a 4,000 Hz square wave to a sawtooth waveform using an RC integrator circuit. This sawtooth is compared to reference voltages to provide pulse width control for the output current. The pulse width control pulses are amplified and applied to the power output transistor, in the power section, which provides the output current for charging the battery. Regulation is achieved by using the voltage signal from the output current shunt as a feedback signal to the control circuit.

Electronic Assembly and Display

The electronic assembly for the display and the display electronics unit are shown in Figure 3. The electrical schematic of the assembly is SKEE 414. The internal PC board interconnection diagram is SKEE 413.

This assembly receives analog signals from the BAC assembly and conditions them to the voltage required by the display readout. The display assembly includes:

- o Signal conditioning section
- o Multiplexer switches
- o Analog to digital (A/D) converter
- o BCD to decimal decoders
- o Solid state read only memory
- o Digital comparators
- o Internal clock and timing pulses generator
- o Alphanumeric projection display

The assembly receives the various analog signals from the BAC and conditions them to the input levels required by the multiplexer. The multiplexer scans all the input signals and applies them to an A/D converter, which provides the output signals for the display readout matrix.

The assembly is capable of operating in three different modes (manual, normal and exceptional) and features high and low limits for each channel. On "manual mode" the channel stepping is operator controlled and the information displayed is updated every 4 seconds.

On "normal mode" the channel stepping is sequentially performed automatically, staying 4 seconds on each channel.

On "exceptional mode" the assembly displays only the measurements that are out of limits (red channels). Each channel is sequentially displayed, and the multiplexer stays 4 seconds on each channel.

Temperature Assembly

The temperature assembly receives a 1.0 vdc signal from the BAC and provides a linear temperature signal to the BAC in accordance with the equation $E_t = -0.00503T + 0.659$. Where $E_t$ is the analog voltage signal proportional to temperature and T is in degrees Centigrade.

Power Transfer Circuit

The power transfer which provides capability for switching the battery voltage onto the bus when bus voltage is below 20 vdc is packaged separately from the BAC. The schematic of the circuit is shown in Figure 13. When the bus voltage is normal, the battery is isolated from the bus by the SCR, and the stop charge output signal is a logic "0" such that the battery will be charged normally. If the bus voltage drops below 20 vdc, the SCR will turn "ON", the battery voltage will be switched to the bus through the SCR, and the stop charge output signal will switch to a logic "1". The stop charge signal would be applied to the BAC stop charge logic to stop the charge while the battery voltage is applied to the bus. When the bus voltage is returned to its normal voltage level, which exceeds the battery voltage, the SCR is cut "OFF" and the system resumes normal operation.

INITIAL SYSTEM OPERATION

The BAC system is initially mated with the battery as follows:

- o Apply input power to the BAC.
- o Operate the display to readout "SOC" with the toggle switch in the manual position and using the advance push-button switch.
- o Adjust the SOC readout value to 100% using the SOC set switch on the BAC. NOTE: SOC switch must be in "NORMAL" position to get correct SOC readout.
- o Charge battery to 100% and connect to BAC.

The input power must be cut off and turned on again in order to reset the system to charge the battery.

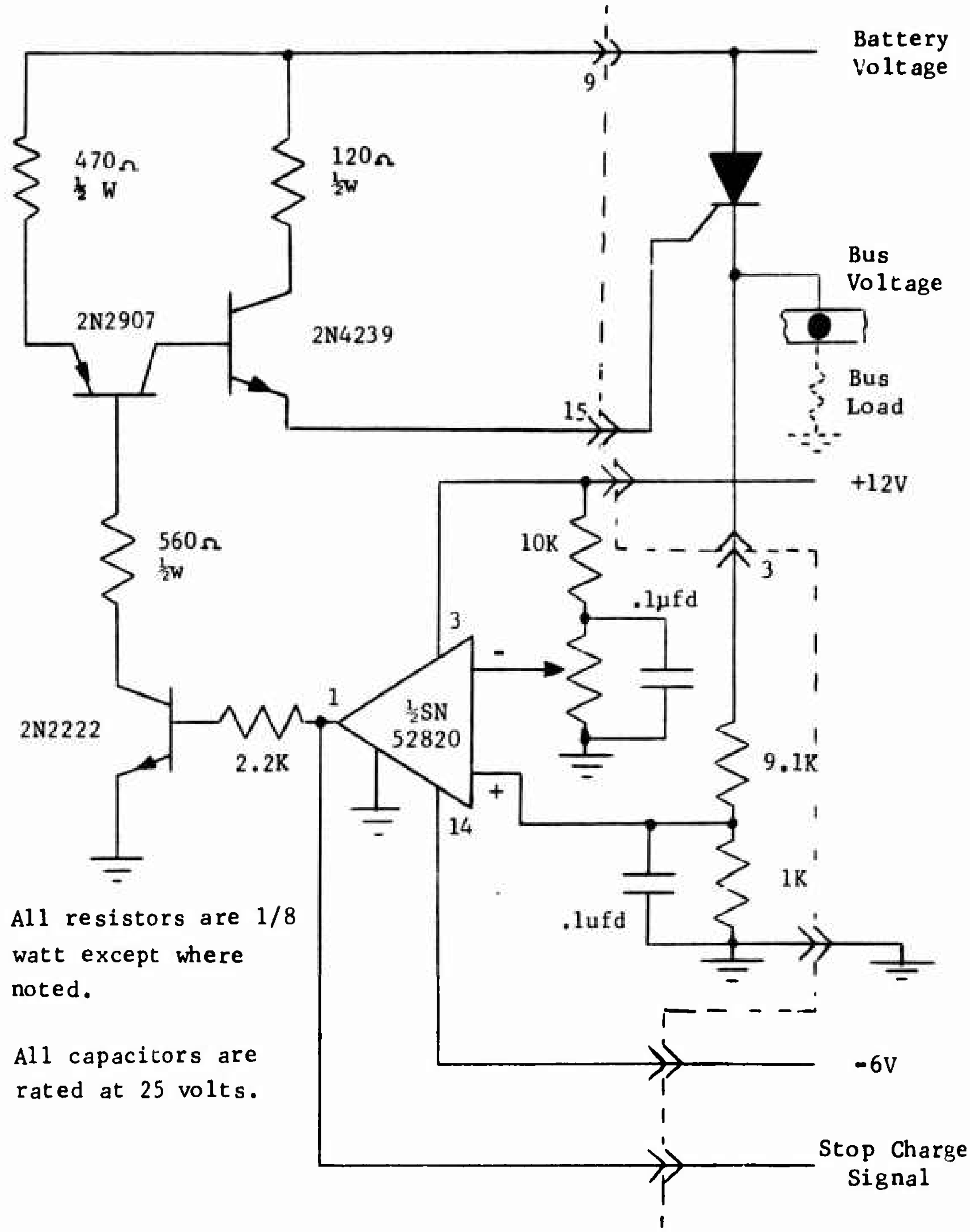


Figure 13. BAC Power Transfer Circuit.

## PERFORMANCE DATA

### GENERAL

Results of the tests on the BAC system are described in the following paragraphs. Tests were performed as follows:

- o Check and adjust various circuits for proper operation.
- o Comparative charge/discharge cycling tests.
- o Limited EMI and temperature.

### CONDITIONER/ANALYZER

During initial checkout of the power section it was discovered that the voltages at the input to the dc-to-dc converters were too high and power resistors were added to reduce the voltages to $28 \pm 4$ vdc.

The power supplies in the power section were adjusted to provide the proper output voltage. The output voltages were periodically checked during testing.

The output power circuit was checked to determine proper operation when a pulse width pulse is applied to the circuit.

All the logic and programming circuitry in the electronic section was checked for proper performance capability and adjusted to the values to be used during the comparative charge/discharge cycle test program. Circuits checked and adjusted included the following:

- o Pulse width modulator
- o System reset at turn-on
- o Cycle count circuits
- o Temperature
- o Charge/discharge amplifiers
- o Charge/discharge integration
- o System reset
- o Current level switching logic
- o Abnormal condition cutoff logic

- 100% cutoff during cycle 10

- 92% cutoff during cycle 0 - 9

- Temperature compensation circuitry

All circuits performed their basic functions properly. The system was checked and adjusted to provide the proper current output profile and PPC programming.

The integrator circuits used in the count circuits and the SOC circuits tended to drift slightly. The resulting effect on normal operation is as follows:

- No effect on charge current profile.

- Approximately 0.1 count/hr drift in the 10-counter. This would result in a PPC profile (see figure 1) where the 100% charge level occurs at 10, +1, -3 cycles rather than 10±1 cycles.

- The SOC readout drifts downward approximately 2%/day during stand time.

DISPLAY AND DISPLAY ELECTRONICS

The circuits in the display electronics were checked and adjusted to the proper levels of operation. All circuits functioned properly. The dwell time for each readout was adjusted to approximately 4.0 seconds.

After the display assembly was integrated with the BAC, the readout parameters were adjusted to read actual input values.

The red background which indicates abnormal conditions operates properly. However, it will illuminate at times other than abnormal conditions due to (a) noise spikes from the power section, (b) out-of-tolerance conditions on unused channels, and (c) channels where the readout values have no upper and lower limits such as the current and count readouts.

TEMPERATURE NETWORK

The temperature compensation network was checked for proper operation.

COMPARATIVE SYSTEM EVALUATION TEST

One of the most important parts of the program was the comparative charge/discharge cycling tests. During this test two 34 AH batteries were cycled under conditions that were identical except for the charging method.

One battery was charged by means of the CCSD prototype PRC system with the current-time profile shown in Figure 1. This battery is designed as PPC in the following discussion. The other battery was charged by the constant-potential method and is identified as CP in the subsequent discussion.

The tests were conducted with the batteries in a nominal ambient temperature of 75°F in accordance with Test Plan PL-EE-73-13.

A charge/discharge cycle, throughout the tests, was defined as the four flight cycle discharge depths shown in Table 5. The profile of the discharge for each flight cycle is shown in Table 6.

Table 5. Flight Cycles Used During Comparative Tests

| FLIGHT CYCLE | DISCHARGE PROFILE (TABLE 6) | DEPTH-OF-DISCHARGE (Percent) | CHARGE TIME (hrs) |
|---|---|---|---|
| 1 | A | 22.1 | 1.33 |
| 2 | B | 22.1 | 2.33 |
| 3 | A | 22.1 | 1.33 |
| 4 | C | 56.4 | 1.58 |

Table 6. Discharge Profiles

| DISCHARGE PROFILE | PREFLIGHT LOAD | | ENGINE START | |
|---|---|---|---|---|
| | MAGNITUDE (amperes) | DURATION (minutes) | MAGNITUDE (amperes) | DURATION (seconds) |
| A | 50 | 4 | 500 | 30 |
| B | 50 | 4 | 500 | 30 |
| C | 50 | 18 | 500 | 30 |

The power supply used for constant-potential charging was rated for 200 adc continuous. Current peaks measured at the start of charging were as high as 500 adc. The voltage was set at 28 ± 0.1 vdc during the latter portion of the charging cycles.

Charging of the batteries was started within 10 seconds after removal of the simulated engine-start load. The elapsed time between flight cycles was no less than 15 minutes.

The battery and cell voltages were continuously scanned during charge and discharge. When the battery voltage dropped below 15 vdc and/or any cell voltage dropped below 0.4 vdc during discharge, the battery was considered to have failed. In this event the battery was reconditioned prior to resumption of cycling. Cells that would not respond to reconditioning were replaced.

Electrolyte level in the cells was checked periodically and water was added when necessary. Records were kept on the amount of water added to each battery.

The cycling tests were discontinued prior to completing 50 cycles because of difficulties experienced with overheating of the CP battery. After 41 cycles it appeared that continuation of the test would be possible onl if several cells were replaced. At this point the PPC battery had been subjected to a total of 45 cycles.

Table 7 is a summary of the cycling test results.

Table 7. Cycling Test Results Summary

| ITEM | TOTALS PER BATTERY | |
|---|---|---|
| | CP BAT. | PPC BAT. |
| Water Added (ml) | 419 | 238 |
| Overtemperature* | 3 | 0 |
| Low Voltage | 13 | 5 |
| Reconditioning Cycles | 8 | 5 |
| Cell Replacement | 5 | 0 |

*Overtemperature of the CP battery occurred during charging following discharge cycles 35-4, 39-2 and 41-1.

## ENVIRONMENTAL TEST

The temperature and EMI tests outlined in the supplemental test plan to PL-EE-73-13 was conducted on the unit with results as outlined herein.

### Temperature

During the temperature testing, the unit operated normally including the charge rate and switching level.

During the temperature test, the battery was not placed in the temperature chamber. Also, the upper temperature was 52°C instead of 55°C since 55°C is 131°F and exceeded the battery cutoff voltage in the specification. The unit operated normally including the charge rate and current switching levels.

## EMI Test

The EMI test was conducted at both the 20 amp and the 3.2A range in accordance with paragraph 3.9 of the supplement to PL-EE-73-13. A photograph of the test setup is shown in Figure 14. The test results are presented in Tables 8 and 9.

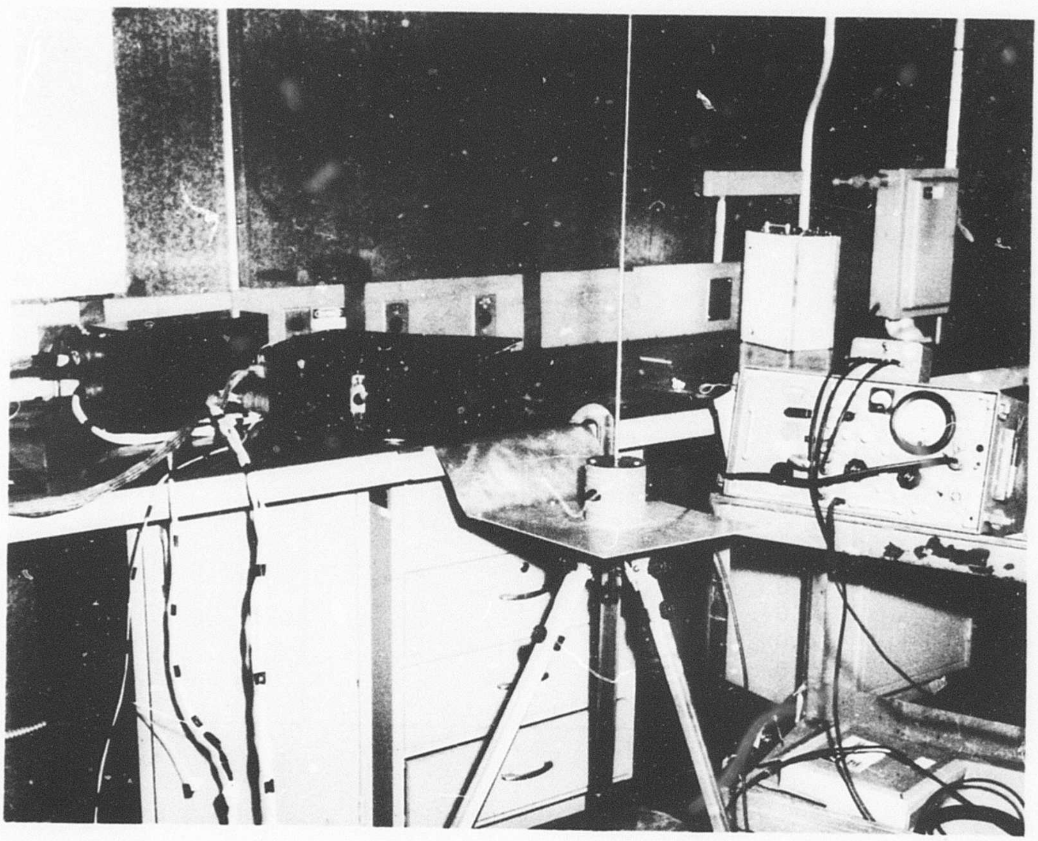

Figure 14. EMI Test Setup.

Table 8. EMI Test Data 20-Amp Level

| TEST FREQ. (mc) | MEASURED LEVEL (db/mv/Mhz) | CORRECTION FACTOR (db) | SIGNAL LEVEL |
|---|---|---|---|
| .15 | 72 | 39 | 111 |
| .30 | 73 | 38 | 111 |
| .40 | 75 | 32 | 107 |
| .50 | 67 | 32 | 99 |
| .60 | 62 | 33 | 95 |
| .70 | 58 | 34 | 92 |
| .80 | 55 | 35 | 90 |
| .90 | 59 | 32 | 91 |
| 1.0 | 57 | 30.5 | 87.5 |
| 1.5 | 52 | 30 | 82 |
| 2.0 | 48 | 32 | 80 |
| 3.0 | 48 | 24 | 72 |
| 4.0 | 61 | 25 | 86 |
| 5.0 | 67 | 26 | 93 |
| 6.0 | 65 | 21.5 | 86.5 |
| 8.0 | 56 | 20 | 76 |
| 10.0 | 72 | 20 | 92 |
| 15.0 | 72 | 19 | 91 |
| 19.0 | 69 | 17 | 86 |
| 21.5 | 80 | 17 | 97 |
| 22.0 | 65 | 17 | 82 |
| 23.0 | 40 | 17 | 57 |
| 25.0 | 48 | 17 | 65 |
| 30.0 | 60 | 16.5 | 76.5 |
| 40.0 | 68 | 8.4 | 76.4 |
| 60.0 | 41 | 8.4 | 49.4 |
| 80.0 | 33 | 8.4 | 41.4 |
| 92.0 | 46 | 9.0 | 55.0 |
| 100.0 | 30 | 9.0 | 39.0 |

Table 9. EMI Test Data 3.2-Amp Level

| TEST FREQ. (mc) | MEASURED LEVEL (db/mv/Mhz) | CORRECTION FACTOR (db) | SIGNAL LEVEL |
|---|---|---|---|
| .15 | 65 | 39 | 104 |
| .30 | 72 | 38 | 110 |
| .40 | 71 | 32 | 103 |
| .50 | 64 | 32 | 96 |
| .60 | 59 | 33 | 92 |
| .70 | 56 | 34 | 90 |
| .80 | 54 | 35 | 89 |
| .90 | 60 | 32 | 92 |
| 1.0 | 60 | 30.5 | 90.5 |
| 1.5 | 55 | 30 | 85 |
| 2.0 | 54 | 32 | 86 |
| 3.0 | 57 | 24 | 81 |
| 4.0 | 61 | 25 | 86 |
| 5.0 | 60 | 26 | 86 |
| 6.0 | 63 | 21.5 | 84.5 |
| 8.0 | 53 | 20 | 73 |
| 10.0 | 58 | 20 | 78 |
| 15.0 | 64 | 19 | 83 |
| 19.0 | 57 | 17 | 74 |
| 21.5 | 70 | 17 | 87 |
| 22.0 | 60 | 17 | 77 |
| 23.0 | 40 | 17 | 57 |
| 25.0 | 44 | 17 | 61 |
| 30.0 | 55 | 16.5 | 71.5 |
| 40.0 | 60 | 8.4 | 68.4 |
| 60.0 | 40 | 8.4 | 48.4 |
| 80.0 | 35 | 8.4 | 43.4 |
| 92.0 | 38 | 9.0 | 47 |
| 100.0 | 35 | 9.0 | 44 |

## RECOMMENDED IMPROVEMENTS

### GENERAL

Although the system performed well and met all requirements, some desirable improvements were identified during the test program. Consideration should be given to incorporation of these improvements in equipment covered by follow-on programs. The following are recommended for consideration:

- o Circuit simplification
- o Elimination of power transient spikes
- o EMI improvement
- o Thermal characteristic
- o Reset system for charger
- o Improved display unit

### CIRCUIT SIMPLIFICATION

Circuit simplification can be achieved both by review of present designed circuitry and use of improved IC circuits with greatly improved circuit density that have recently become available.

### ELIMINATION OF POWER TRANSIENT SPIKES

Improved circuit design and grounding schemes should be used to eliminate the effect of the transient power spikes from the pulse width modulating system from being coupled into other circuits in the BAC.

### EMI IMPROVEMENT

Precautions must be taken in both design and packaging techniques to reduce the level of EMI radiation from the BAC due to the pulse width modulation system.

### IMPROVED DISPLAY UNIT

A more simplified and ruggedized display unit must be used for BAC's to be used as flight hardware.

### RESET SYSTEM FOR CHARGER

The charger resets only when the power is cut off and reapplied. The charger should have a reset switch to reset the charger without requiring power cutoff. It should also automatically reset when the battery is switched on the "bus" during emergencies where the bus voltage has a temporary failure.

## Thermal Characteristic

The BAC should have a blower or should be reconfigured to improve heat dissipation if the mounting compartment does not contain proper air currents to prevent heat pockets within the BAC installation compartment.

## Conclusions

The data in Table 7 clearly shows that the PPC system provides the following advantages over the constant-potential system.

- o Increased battery life
- o Reduced maintenance
- o Hazard elimination

The increase in battery life cannot be quantitatively expressed, since none of the cells in the PPC battery were replaced. However, the increase must be considered significant since 5 of 19 cells in the CP battery were replaced.

Reduction in maintenance is indicated by the amount of water added and the number of reconditioning cycles. The CP battery required 176 percent more water and 160 percent more reconditioning cycles than did the PPC battery.

Elimination of hazards is illustrated by lack of PPC battery overheating due to thermal runaway, while the CP battery overheated three times.

The advantages of the PPC system would be greater if the ambient temperature were higher than the 75$^{o}$F level used for this evaluation. The tendency toward water loss, thermal runaway, and cell failure is greater at elevated temperature.

The improvements in battery performance caused by the PPC system are considered to be due to the following:

1) Limiting of charging current when charging is first started.

2) Reducing the charging current in steps.

3) Limiting the time during which maximum voltage is applied.

Items 1) and 3) seem to be self-explanatory. The benefit from 2) is not obvious, but is significant. Reduction of charging current in steps, with corresponding reduction in battery voltage, reduces cell voltage imbalance. When the charging current is reduced, the cells with lower SOC can be charged without causing the voltage of cells with high SOC to exceed the critical value.

## APPENDIX A

## SUMMARY OF PREVIOUS REPORTS AND ANALYSES

### GENERAL SUMMARY

A summary of the following analyses presented in the design review of October 26, 1972 is presented in Tables 10 through 12.

- o Comparison of methods applicable to vented cell batteries.
- o Comparison of Nickel-Cadmium and Lead-Acid battery capabilities. (Batteries intended for engine start applications).
- o Comparison of Nickel Cadmium and Lead-Oxide battery capabilities (sealed battery not intended for engine start applications).

TABLE A-1. COMPARISON OF CHARGING METHODS AS APPLICABLE TO VENTED CELL BATTERIES

| METHOD | PRINCIPLE OF OPERATION | EFFECT ON BATTERY PERFORMANCE | | | CHARGER CONSIDERATIONS | SYSTEM CONSIDERATIONS |
|---|---|---|---|---|---|---|
| | | MAINTENANCE | CYCLE LIFE | OPERATIONAL CAPABILITY | | |
| TRUE CONSTANT POTENTIAL | BATTERY CHARGED AT CONSTANT VOLTAGE - INITIAL CHARGE CURRENT LIMITED ONLY BY SOURCE & LINE IMPEDANCE. | MAX ELECTRO-LYTE LOSS EACH CYCLE | NO REDUCTION OF MEMORY EFFECT | FAST RECHARGE POSSIBLE | SIMPLE DESIGN | DOES NOT REQUIRE CLOSELY MATCHED CELLS. |
| CONSTANT POTENTIAL CONSTANT CURRENT | BATTERY CHARGED AT TEMPERATURE COMPENSATED VOLTAGE - CURRENT LIMITED INITIALLY BY BATTERY CONSIDERATIONS. | ELECTROLYTE LOSS EACH CYCLE | NO REDUCTION OF MEMORY EFFECT | FACILITATES QUICK RECHARGE | REQUIRES BATTERY TEMPERATURE SENSOR<br>REQUIRES WIDE RANGE OF POWER HANDLING CAPABILITY<br>REQUIRES GOOD MATCHING OF CHARGER VOLTAGE TO BATTERY CHARACTERISTICS IN OVERCHARGE TO AVOID THERMAL RUNAWAY OF NICKEL CADMIUM CELLS. | DOES NOT REQUIRE CLOSELY MATCHED CELLS. |
| MULTI-LEVEL CONSTANT CURRENT | BATTERY CHARGE IS REDUCED AS STATE OF CHARGE INCREASES. | ELECTROLYTE LOSS EACH CYCLE | NO REDUCTION OF MEMORY EFFECT | REQUIRES LONGER RECHARGE TIME THAN CONSTANT POTENTIAL. | REQUIRES BATTERY TEMPERATURE SENSOR<br>REDUCED POWER HANDLING CAPABILITY AS OPPOSED TO CONSTANT POTENTIAL METHOD<br>DIFFICULT TO DETERMINE OPTIMUM CHARGE TERMINATION CONDITION | REQUIRES CELLS CLOSELY MATCHED FOR CAPACITY |
| PROGRAMMED PEAK CHARGE (PPC) | CHARGING IS CONTROLLED OR PROGRAMMED SO THAT BATTERY IS ONLY RETURNED TO FULLY CHARGED CONDITION PERIODICALLY. FREQUENCY IS DETERMINED BY ACCURACY OF STATE-OF-CHARGE SENSING DEVICE WHICH MUST BE PERIODICALLY RESET TO NULL OUT ERRORS. | ELECTROLYTE LOSS ONLY WHEN BATTERY RETURNED TO FULLY CH'D CONDITION | VARIATION IN PEAK STATE-OF-CHARGE WILL ALLEVI-ATE MEMORY CONDITION. | FAST RECHARGE POSSIBLE ON CYCLE WHEN BATTERY IS NOT FULLY CHARGED. | REQUIRES BATTERY TEMPERATURE SENSOR<br>REQUIRES INTEGRATING DEVICE FOR AMPERE-HOUR INPUT-OUTPUT MONITORING<br>REQUIRES COMPENSATION FOR CHARGE EFFICIENCY AND POSSIBLY STAND LOSSES | REQUIRES CELLS MATCHED CLOSELY FOR CAPACITY |
| PULSE CHARGING (CHRISTIE TECHNIQUE) | CHARGER PROVIDES A REVERSE CURRENT PULSE AFTER EACH HEAVY CHARGING PULSE TO CAUSE DEPOLARIZATION OF THE BATTERY PLATES TO ALLOW BETTER ABSORPTION OF THE CHARGING CURRENT | ELECTROLYTE LOSS EACH CYCLE | | SHOULD REDUCE CHARGE TIME SINCE HIGHER CHARGE RATES CAN BE USED AS COMPARED TO CONSTANT POTENTIAL | REQUIRES HIGH POWER HANDLING CAPABILITY. | REQUIRES CELLS MATCHED CLOSELY FOR CAPACITY<br>POSSIBLE EMI PROBLEMS<br>POSSIBLY REQUIRES BATTERY REDESIGN FOR MOST EFFEC-TIVE UTILIZATION |
| PULSED CONSTANT CURRENT (UTAH RES. & DEVEL. CO.) | CHARGE CURRENT CONSISTS OF PULSE OF CURRENT WHOSE PEAK VALUES MAY BE AS HIGH AS 500 AMPS, WHILE CONTROLLING THE DUTY CYCLE TO OBTAIN THE DESIRED AVERAGE VALUE OF CURRENT | ELECTROLYTE LOSS EACH CYCLE | | SHOULD REDUCE CHARGE TIME AS COMPARED TO CONSTANT POTENTIAL | REQUIRES HIGH POWER HANDLING CAPABILITY. | REQUIRES CELLS MATCHED CLOSELY FOR CAPACITY.<br>POSSIBLE EMI PROBLEMS |

TABLE A-2. COMPARISON OF NICKEL-CADMIUM AND LEAD-LEAD DIOXIDE BATTERY CAPABILITIES (SEALED BATTERY NOT INTENDED FOR ENGINE START APPLICATIONS)

| PARAMETER | | NICKEL-CADMIUM (SEALED) | LEAD-LEAD DIOXIDE (SEALED) | REMARKS |
|---|---|---|---|---|
| CAPACITY | | 12 AH AT 2 HR RATE | 11 AH AT 1 HR RATE | |
| NO. CELLS/24 V BATTERY | | 19 | 12 | FEWER CELLS, INCREASES RELIABILITY FOR LEAD-ACID BATTERY. |
| WEIGHT (24 V) | | 22 LB | 33.5 LB | NI-CAD HAS MUCH GREATER ENERGY |
| VOLUME | | 240 $IN.^3$ | 435 $IN.^3$ | DENSITY |
| CYCLE LIFE | | 1000 TO 15,000 CYCLES | 200 TO 500 CYCLES | NI-CAD HAS MUCH GREATER CYCLE LIFE CAPABILITY |
| MAX RECHARGE RATE | | LIMITED BY CHARGER CONSIDERATIONS | 3 AMPS (0.27C) | NI-CAD CAN BE RECHARGED FASTER. |
| OVER-CHARGE CAPABILITIES | | 1.5 AMP CONTINUOUS | LIMITED | |
| MAX DISCHARGE RATE | | 120 AMP CONTINUOUS | 100 AMP | |
| STAND LOSSES | | 0.3 TO 2%/DAY AT 20°C | 0.1%/DAY AT 20°C | COMPARABLE |
| OPERATING TEMP. | DISCHARGE | -10°C TO 40°C | -60°C TO 60°C | |
| | CHARGE | - 10°C TO 40°C | -20°C TO 50°C | |
| CAPACITY REDUCTIONS AT TEMP OTHER THAN 25°C | 60°C | 1.2 TO 6.5% DAY | +14% | NI-CAD PERFORMS MUCH BETTER AT LOW TEMPERATURE. |
| | -50°C | 35% | 75% | |
| MEMORY EFFECTS | | EXHIBIT MEMORY | NONE | NI-CAD WILL REQUIRE RECONDITIONING FOR OPTIMUM PERFORMANCE. |

TABLE A-3. COMPARISON OF NICKEL-CADMIUM AND LEAD ACID BATTERY CAPABILITIES
(BATTERIES INTENDED FOR ENGINE START APPLICATIONS)

| PARAMETER | | | VENTED NICKEL-CADMIUM | VENTED LEAD ACID | REMARKS |
|---|---|---|---|---|---|
| CAPACITY | | | 34 AH (2 HR RATE) | 36 AH (5 HR RATE) | |
| NO. CELLS/24 V BTRY | | | 19 | 12 | LEAD ACID ADVANTAGE - FEWER CELLS, INCREASED RELIABILITY |
| WEIGHT (24 V) | | | 80 LB | 80 LB | |
| VOLUME | | | 1070 $IN^3$ | 1750 $IN^3$ | NI-CD IS APPROXIMATELY 40% SMALLER |
| CYCLE LIFE | | | 500 TO 5000 CYCLES | 10 TO 400 CYCLES | NI-CD OFFER GREATER CYCLE LIFE - MAY REQUIRE RECONDITIONING |
| | | | | | |
| VOLTAGE VS TEMP. COEFFICIENT | | | NEGATIVE | POSITIVE | NI-CD MAY EXHIBIT THERMAL RUN-AWAY AT CONSTANT POTENTIAL CHARGE |
| DISCHARGE | 25°C | 5 MIN RATE | 240 AMP/20 A-H | 180 AMP/15 AH | NI-CD CAN SUPPLY 33% MORE CAPACITY AT HIGHER CURRENT RATE |
| DISCHARGE | -18°C | PEAK CURRENT | 320 AMP FOR 4.6 MIN (24.5 AH)<br>775 AMP FOR 20 SEC 3 TIMES AT 2 MIN INTERVALS (13 AH) | 180 AMPS FOR 3 MIN (9 A-H)<br>(900 AMP FOR 45 SEC ) (11.3 A-H) | NI-CD IS CAPABLE OF SUPPLYING MORE ENERGY AT LOW TEMP. |
| CAPACITY REDUCTIONS AT TEMP. OTHER THAN 25°C | -40°C | | 30 TO 50% REDUCTION | 70% REDUCTION | NI-CD IS CAPABLE OF SUPPLYING MORE ENERGY AT LOW TEMP. |
| | +50°C | | 5 TO 20% REDUCTION | NEGLIGIBLE REDUCTION | |
| STAND LOSSES | +50°C | | 1.2 TO 6.5%/DAY | 1 TO 7%/DAY | COMPARABLE |
| MEMORY EFFECTS | | | YES | NOT APPLICABLE | NI-CD REQUIRES PERIODIC RECONDITIONING |

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